Test of Prototype Power Leads HINS_CH_LDHTS_02

M. Tartaglia, C.Hess, S. Feher, F. Lewis, D. Orris, T.Page, R. Rabehl

Introduction

In this report, the assembly and test of the second pair of Ag-BSSCO(2223) HTS evaluation leads, built by HTS-110, is described. An introduction to the program and test results of the first pair (built by Cryomagnetics, Inc.) is described in [1]. The cold test took place in the IB1 stand 3 dewar on November 27, 2007.

Device and Apparatus

Resistive Section Design

The same upper resistive section used in the first HTS leads assembly, hins_ch_ldhts_01, was re-used for this test. A slight modification was required to make the connection to the HTS-110 leads: the indium solder connection was removed, and a bolt-on connection was made instead. The copper contact surfaces were tinned with solder prior to making the connection, to lower the joint resistance. The LTS splice was made the same way as in [1]. Figure 1 shows a photograph of the bolted joints and temperature sensor locations.

The instrumentation list was similar to the first leads test assembly, differing only in the voltage taps across the HTS section (V3 does not exist, no redundant V4 tap). Figure 2 shows the arrangement of Platinum RTD and Voltage Tap sensors on the power leads. A photograph of the final lead assembly with a mechanical dimension map is also shown in Figure 2.

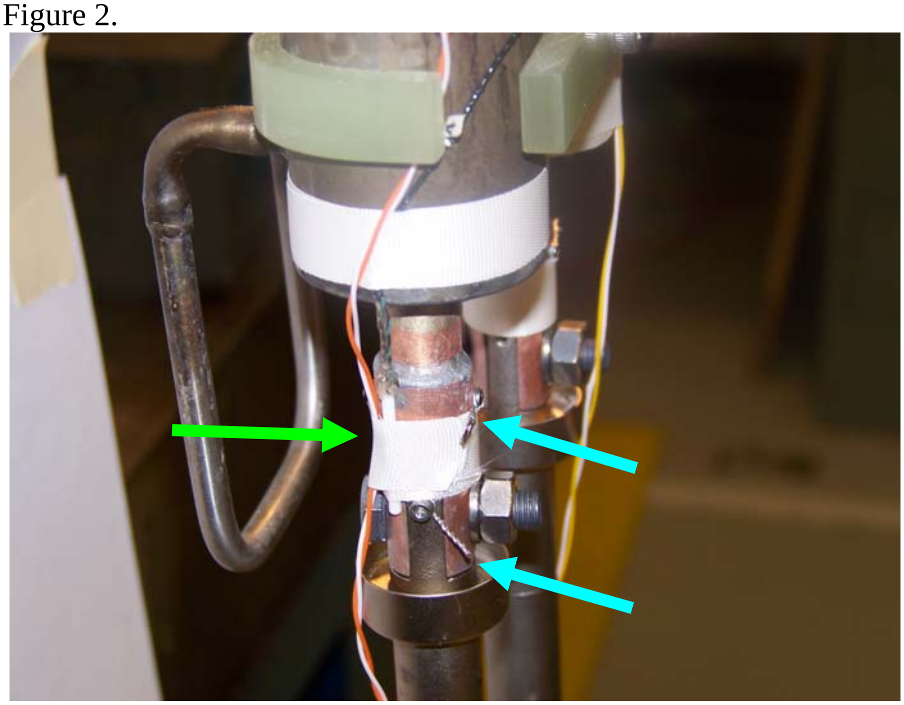

Figure 1. Green arrow shows Pt temperature sensor location below the LN2 heat exchangers at the bottom copper/upper HTS section of the leads. Blue arrows show voltage taps V2 and V5 that span the bolted joint.

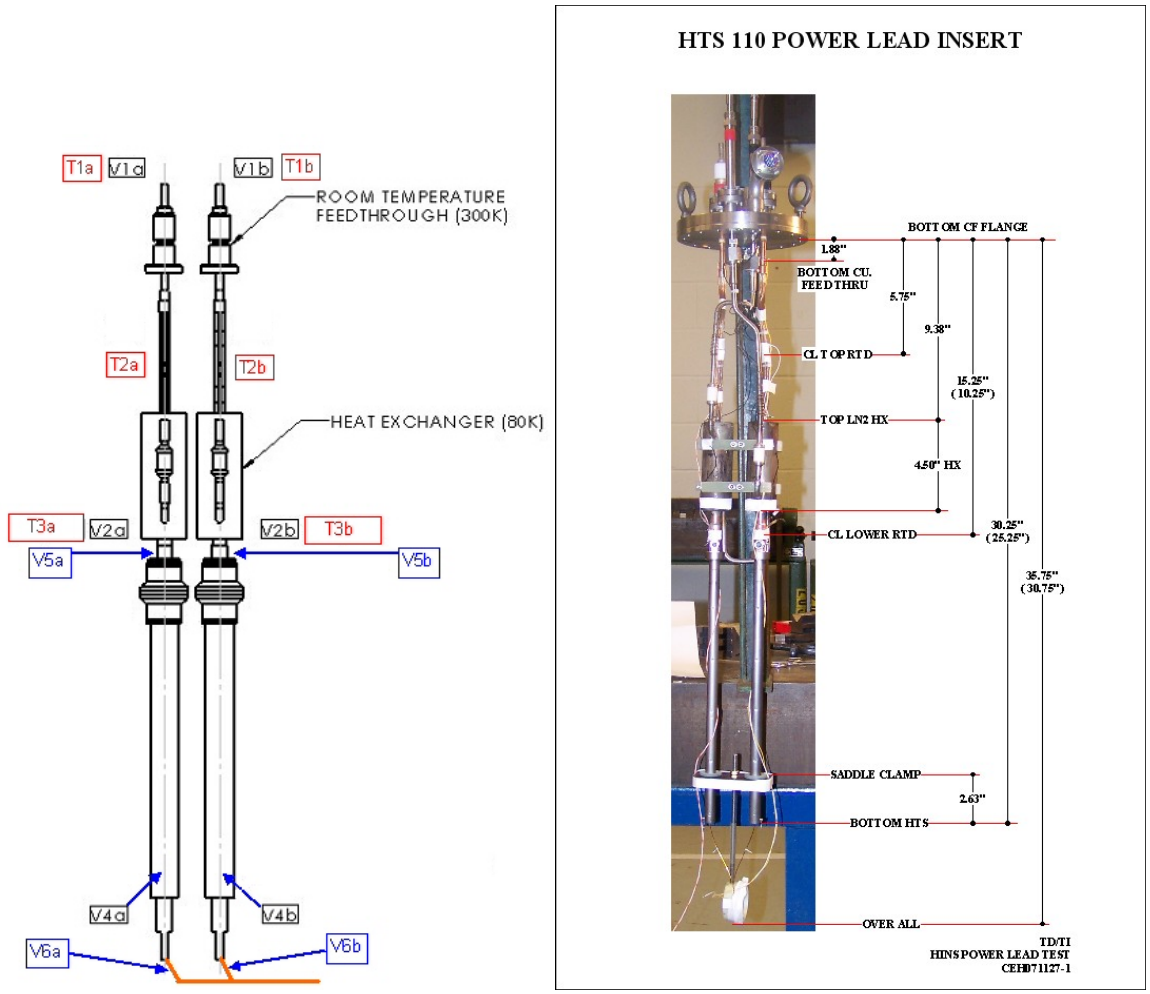

Figure 2. Leads with Voltage Tap and Temperature Sensor Instrumentation, and photo of HTS-110 leads assembly with dimensions prior to cold test; dimensions are in inches.

We opted to make the power and LN2 flow scheme for this test identical to the first test (see Figure 2 in [1]). Again, Lead A was connected to the Positive power supply terminal, and Lead B was connected to the Negative terminal. Liquid Nitrogen was supplied to the Negative lead (B). The 12” level probe was positioned with the bottom end of the probe 6” from the bottom of the HTS leads.

Cold Test Procedure and Test Results

The detailed cold test chronology is included as Appendix I. Figure 3 gives an overview of the lead temperatures, LN2 flow, current and liquid level during the entire test. A summary of the “equilibrium” thermal conditions is shown in Table 1.

Thermal Measurements

We first established the minimum required LN2 flow to maintain the warm end of the HTS section (bottom end of the resistive section) at 82K at 0A. (The actual sensor and voltage tap locations at the joint are shown in Figure 1). In this test, the temperatures on the two leads were in very good agreement and did not fall below the 82K point. They were insensitive to the helium level, exhibiting no difference at 6” versus 7”. Most measurements were made with the helium liquid level set to 7” (17.5 cm), or one inch above the bottom of the HTS/LTS flag. The N2 flow was measured with a flow transmitter (FT519 in IFIX database) and by the rotameter used for flow control. Although FT519 has been used in the past, we noticed there is a large discrepancy with the rotameter, as shown in Figure 4: it appears to read about 50% high (we assume the mechanical rotameter is more reliable, although there is clearly an offset at low flow). We note this discrepancy, and plan to recalibrate this transmitter; nevertheless we report here the flows recorded by this transmitter and recognize that they are probably over-estimates of the true required flow (note also that these will again be measured in production lead tests). We showed reproducibly that a minimum LN2 flow of 1.9 g/s is required (vs. 1.0 g/s predicted) to maintain the HTS warm end at 82 K. A higher-than-expected flow might arise due to a) inefficient heat exchanger, or b) additional sources of heat to the N2 circuit (e.g., some conduction through tubing).

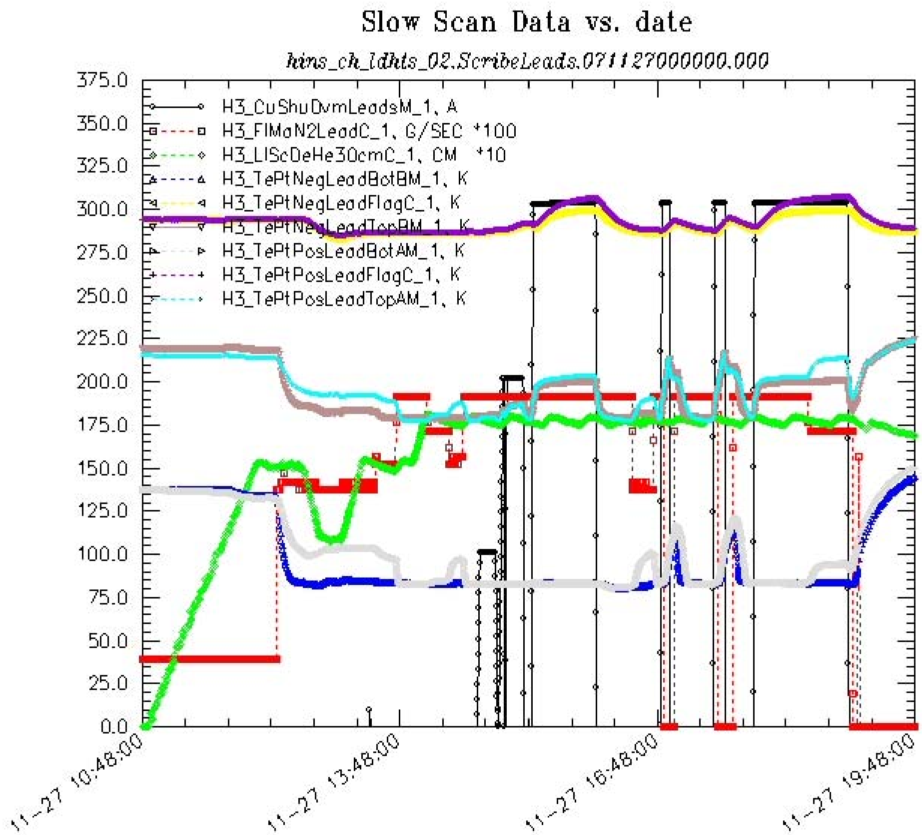

Figure 3. Overview of LN2 flow, liquid level, current, and resistive section (flag, top, bottom) lead temperatures versus time, during the entire cold test.

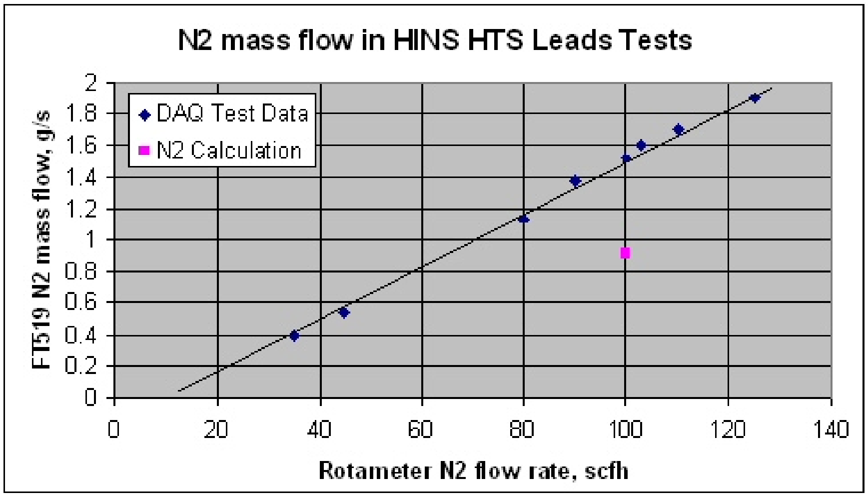

Figure 4. Comparison of Flow Transmitter versus Rotameter mass flow rates, and expected value at 100 scfh.

Note that the helium supply valve to stand 3 was set in "Top Fill" mode for the entire test, except for the initial fill and a brief period to test the effect of filling in "Bottom Fill" mode. This clearly showed that Bottom Fill causes the lead temperatures to fall (although not nearly as much as in the previous leads test), as convection promotes additional helium cooling of the leads. Liquid level clearly showed more scatter when in Bottom Fill mode. The Top Fill option acts as a phase separator, allowing gas to separate from the two-phase helium above the liquid level.

Based upon experience from the first leads evaluation test, and for lack of time, we did not attempt to make measurements of heat loads to the helium bath by looking at boil-off rates. (This may be best done in tests using the actual cryostat).

The resistive sections performed well in power testing at 300A. The required minimum LN2 flow at 300A was also 1.9 g/s. The flag temperatures were about 286 K in standby mode, and rose to a stable temperature of 300-305 K at 300 A. Temperatures in the middle of the resistive section were also stable but sensitive to LN2 flow (Fig. 5).

Table 1. LN2 flow and "equilibrium" temperature conditions at HTS warm end

Time line / action	LN2 mass flow [g/s]	Differential Pressure [psia]	Neg. lead temp. T3b [K]	Pos. lead temp. T3a [K]
Initial cool down	1.37	.46	84.1	103.5
Raise flow, LL=6"	1.51	.58	83.4	97.5
Raise flow	1.90	.78	82.9	82.7
Raise LL to 7"	1.90	.78	82.7	82.7
Reduce Flow	1.70	.65	82.7	84.7
Reduce Flow	1.51	.55	83.0	96.9
Raise Flow	1.90	.78	82.6	82.6

Ramps to 100 A, 200 A and 300 A for resistance measurements.				
Hold @ 300A for 40 min.	1.90	.78	83.1	83.1
Switch to Bottom Fill Mode				
Hold at 0A	1.90	.78	80.7	81.5
Reduce Flow	1.37	.45	82.5	100.7
Return to Top Fill Mode; perform loss-of-coolant test				
Restore Flow	1.90	0	82.7	82.7
Ramp to 300 A	0	Quench detected (1mV), Neg. Lead at 100K		
Repeat above	0	Quench detected (2mV), Neg. Lead at 103K		
Test Performance following quench at normal and reduced flow				
Hold @ 300 A for 30 min.	1.90	.86	83.1	83.1
Hold @ 300 A for 30 min.	1.71	.71	83.3	94.4

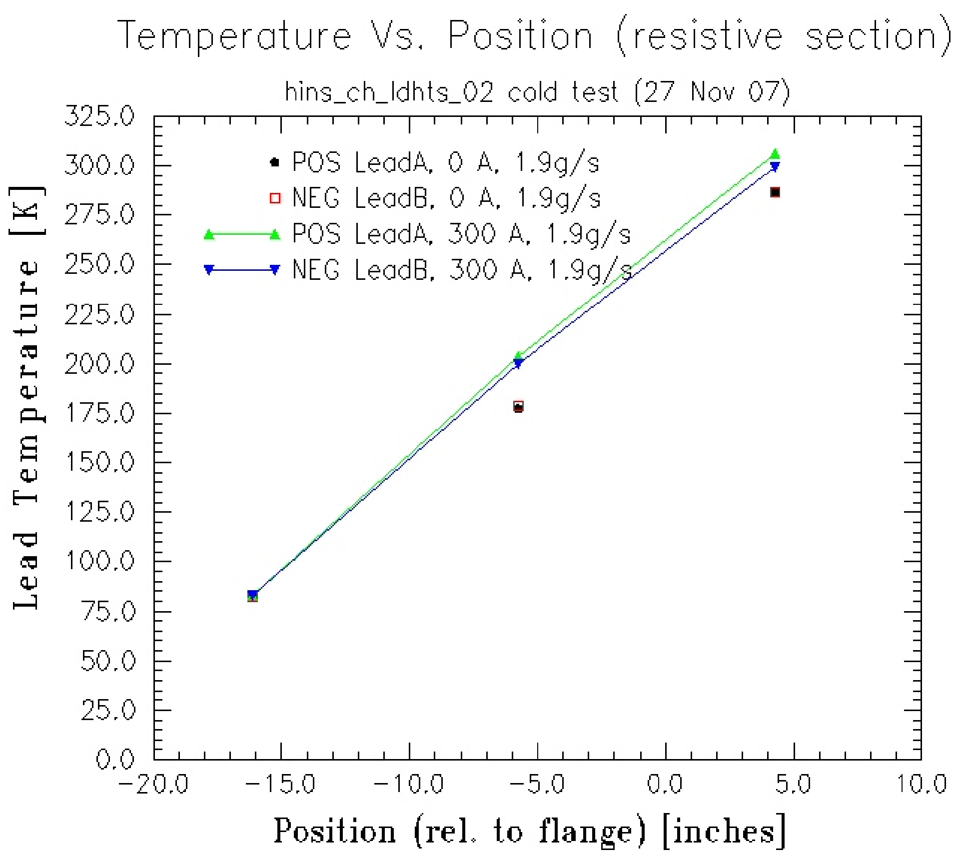

Figure 5. Resistive section temperature profile, at the minimum required flow condition in standby and when powered at 300A.

Voltage Measurements

A summary of the joint resistance values is shown in Table 2. Voltages across the lead segments were measured with a HP 3458 DVM, integrating over a power line cycle, after amplification with the “MTF_Isoamp” fully programmable vme-based amplifiers and multiplexed through a standard HP 1351 FET multiplexer. All of the “resistive” voltage tap segments showed linear behavior with current and were easily fit to obtain the resistances. The LTS splice segment was close to being consistent with no resistance.

Table 2. Resistances of the Current Lead Segments

Segment	Location	Gain Used	R(Pos. Lead A) [μΩ]	R(Neg. Lead B) [μΩ]
V1V5	Copper Section	10	165.6 ± 0.1	165.0 ± 0.1
V2V5 (83K)	Bolted Solder Joint	200	6.355 ± 0.006	9.867 ± 0.007
V4V6	HTS/LTS Joint	10	0.456 ± 0.008	0.468 ± 0.002
VSplice	LTS Splice	1000	-0.011 ± 0.003	

Both HTS segments became resistive during the LN2 coolant-loss quench events. Figure 6 shows the time dependence of the HTS segment voltages during powering: the voltages respond linearly to current due to internal joint resistance, and non-linearly due to temperature rise of the HTS material when N2 flow is reduced to zero at 300A, leading to the HTS quench.

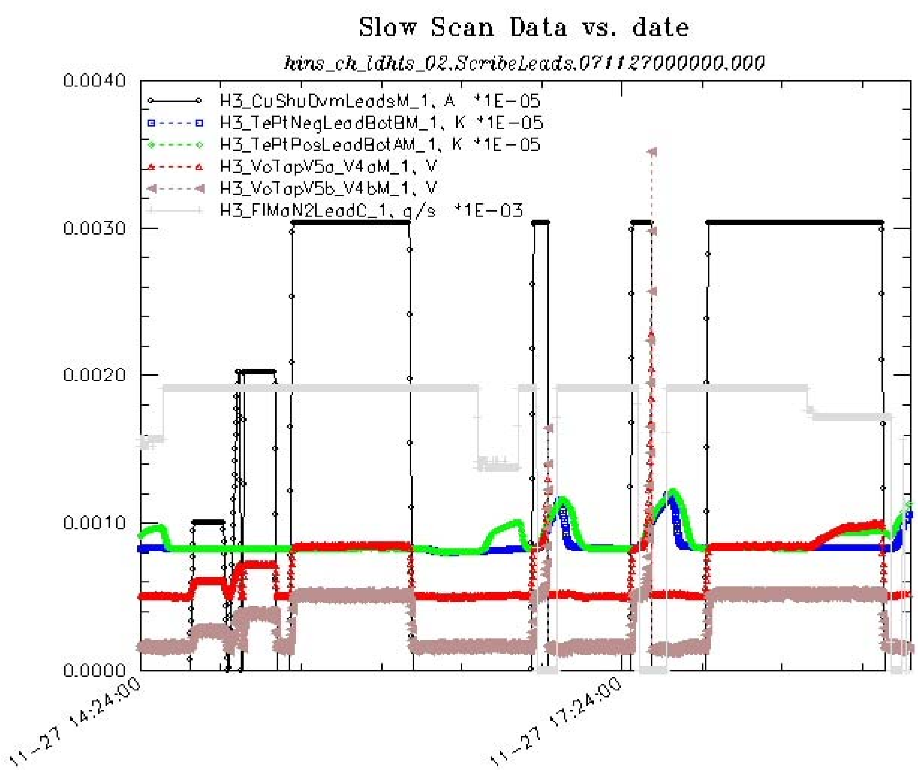

Figure 6. Time dependence of Current, LN2 flow, HTS warm end temperatures, and HTS voltages during the power testing.

In Figure 7, the HTS voltage is shown as a function of the HTS section warm end temperature. The lower horizontal lines represent thermal EMFs during periods of un-powered operation. Ramps at different temperatures appear as (near) vertical lines due to the internal joint resistance. As the temperatures rise at high current, the voltages follow a steadily rising trajectory, fairly rapidly reaching the quench threshold at 300 A. The coolant loss/quench test was performed twice: first with a 1mV quench detection threshold, which appeared in the captured quench data to have occurred at -0.6mV. In the second try, the half coil threshold was raised to 2mV, and the captured data indicated -1.6mV, confirming that the quench was real, but with a small offset in the voltage signal. In both events, the negative lead voltage grew faster than the positive lead, even though it was slightly cooler at the heat exchanger end. As with the Cryomagnetics leads [1] this probably indicates some variation in the current margin of the HTS-110 leads.

Following the quench event, LN2 cooling flow was re-established, and the leads were again powered to 300 A, demonstrating that no degradation had occurred. After 30 minutes of stable operation, the LN2 flow was reduced to 1.7 g/s to determine whether the leads had some temperature margin. The positive lead temperature increased to 94 K after 30 minutes, and the lead continued to operate at 300 A without any problems.

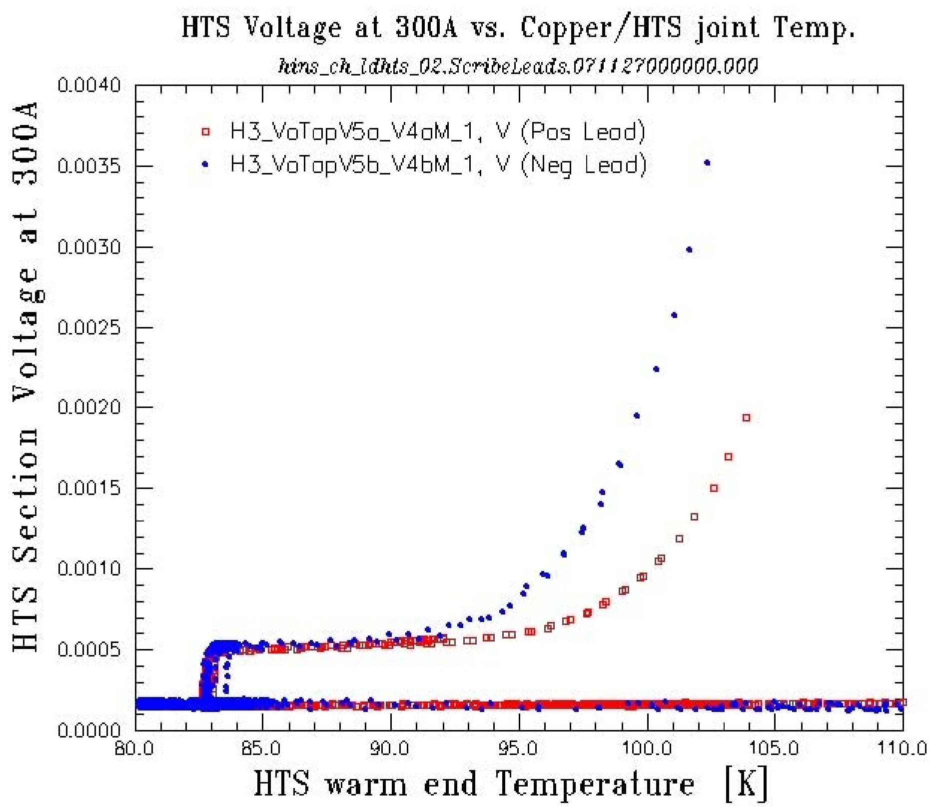

Figure 7. Voltage across the HTS section when powered at (up to) 300 A, as a function of the temperature at the warm end of the lead.

Conclusions

The performance of the upper resistive section was successful. Temperatures on both leads were very consistent, and the flag temperatures were stable and fairly insensitive to the LN2 cooling conditions. The measured minimum required LN2 flow is better estimated in this test than in [1] because of less helium convection within the stand 3 dewar (by using the inlet valve in Top Fill mode): the result was about 1.9g/s, nearly twice the predicted requirement, for both standby and 300A powered modes.

The HTS-110 leads performed well in this test, and met specifications. They operated without any voltage growth for long periods at 300 A with the minimum required LN2 cooling flow maintaining the warm end temperature at about 82K. During the coolant loss test the temperatures rose above the required minimum 82K level to about 100 K, at which point one (Neg.) lead quenched. Following two such quench events, the leads performed successfully without signs of degradation. In a subsequent reduced flow performance test (1.7 g/s) the positive lead reached 94 K without quenching, thus demonstrating a fair level of operating margin.

References

[1] M. Tartaglia, I. Terechkine, T.Page, D. Orris, F. Lewis, C.Hess, R. Rabehl, "Test of Prototype Power Leads HINS_CH_LDHTS_01", FNAL Technical Division Note TD-07-029, 28 December, 2007

Appendix I. HINS_CH_LDHTS_02 Cold Test Chronology on 11/27/07

07:15 Start Transfer of liquid Helium to stand 3 dewar
Start LN2 flow at 0.5g/s to lead heat exchangers
(it dropped slightly to .4 g/s, 35scfh)
Kepko PS is turned on (toggling +/- 0.5A)
08:00 LN2 shield temperature reaches 82K
08:30 Kepko PS is turned off – voltages are all quite small
~11:30 Hi-pot to 1000V successfully completed; Power leads connected
12:08 He LL is at 15cm (6") on 30cm probe = bottom of the HTS leads
12:20 TbotA and TbotB are at about 103K; Raise LN2 flow to 90 scfh = 1.37g/s
Flag Pt sensors are re-attached after hi-pot; Tflags ~282K
12:38 First helium dewar empty
12:59 Second 500 liter dewar in on line
13:23 Helium liquid level reaches 15cm again (=bottom of HTS section)
We are in TOP FILL MODE (earlier we were in BOTTOM FILL MODE):
Note change in liquid level stability
10A trip performed to check PS/QD/QC system
TbotA = 103, TbotB = 84
13:31 Raise leads LN2 mass flow to 100 scfh = 1.52 g/s
Bottom temperatures stabilize at 84K(B,-) and 98K(A,+)
13:45 Raise LN2 mass flow to 125 scfh = 1.9 g/s
Bottom temperatures quickly fall, both settle at 83K
13:56 Note: LL is at 6", bottom of HTS; we need to raise it to 7" level

14:05 LL is at 7" – no change in Lead Bottom temperatures
14:07 We are trying to understand what is so different w/temperatures from the first test,
So we lower LN2 flow again to 110 scfh = 1.7g/s
Temperature on Lead A rises slightly to 84K, LeadB stays at 83K
14:22 Lower LN2 flow again to 100 scfh = 1.5g/s
Lead A bottom temperatures reproduces earlier level at this flow: 96K
Therefore, we decide that the **minimum required flow is 1.9g/s**
[dP on Magnahelic gauge reads 19" H2O; dP transmitter reads 0.65 psi]
14:40 Ramp PS to 100A, hold for 10 minutes. There is a slight rise in TtopA and B, which agree nicely with each other (as do TbotA and B)
Note: QD "Whole Coil" signal is actually V5a_V6a + V5b_V6b = sum of HTS voltages, with 10mV threshold; noise level is about +/- 2mV
"Bucked Half Coil" signal is V5a_V6a – V5b_V6b, with 1mV threshold; signal has about -0.2mV offset, and noise level of +/- 0.2mV, with 1ms filter on the input.
14:58 Ramp to 200A; by mistake, we went up and down with 30 s flat top
15:03 Ramp again to 200A (5A/s), hold for 10 minutes
15:19 Ramp to 300A; hold for 45 minutes to watch stability of copper lead temperatures
Bottom temperatures rise to 104K(A) and 103K(B); Top temps are about 300K.
16:05 Ramp to 0A. Note there is a slight drop in Lead Bot Temp's from 83 to 82.5K
Try an experiment to understand difference vs test of ldhts_01:
16:10 Switch helium supply valve from TOP FILL to BOTTOM FILL on dewar
Lead Bottom temperatures both fall quickly to 80K, then slowly rise about 1K (and diverge by about 0.2K)
Note also that LL becomes obviously more "noisy"
16:30 While still in BOTTOM FILL mode, lower the LN2 flow to 90 scfh = 1.37g/s
This is similar to the ldhts_01 test condition
TbotA temperature rises to 96K, while TbotB temperature remains at 81K
16:40 Return to TOP FILL MODE with LN2 flow at 1.37g/s
Temperatures rise, as expected, to 100K(A) and 83K(B)
16:45 Restore LN2 flow to 1.9g/s (125 scfh), stabilize temperatures for more power tests
16:50 Ramp to 300A at 5A/s, hold for ___ minutes
16:52 Begin Loss Of Coolant Test: turn LN2 flow to zero
16:56:25 Quench Detected by Half Coil signal at 1mV – QC data show -0.6mV
Lead B voltage growth is faster than Lead A (consistent with above)
Temperatures continued rising – to about 101K – until LN2 flow restored
17:26 Ramp to 300A at 5A/s; raise QD threshold to 2mV
17:30 Repeat Coolant Loss Test: Turn LN2 flow to zero
17:35:08 Quench Detected by Half Coil signal at 2mV (it had been slowly growing in the negative direction) – QC data show -1.6mV, ➔ 0.4mV offset
Again, Lead B voltage growth is faster (consistent)
17:40 Restore LN2 flow to 1.9g/s, recover Tbot temperatures to 83K
17:55 Ramp to 300A at 5A/s, hold for 40 minutes, to demonstrate no degradation
Leads are operating stably
18:33 Lower LN2 flow to 1.7g/s, to demonstrate operating temperature margin
Continue operating at 300A for additional 30 minutes

	TbotA rises to 94K, TbotB remains at 83K, no quench occurs.
19:00	Ramp to 0A
19:05	LN2 flow is off; Test Ended